# New method for continuous monitoring of concrete E-modulus since casting using an output-only modal identification technique

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ABSTRACT: A new methodology that allows the continuous measurement of concrete E-modulus since casting is presented in this paper. This methodology is a variant to the classical resonant frequency methods, which have the downside of requiring concrete to be de-mouldable and withstand mechanical impact to start testing. The proposed experimental setup comprises a simply supported beam made-up with an acrylic tube, filled with the concrete to be tested, whose mid-span vertical accelerations induced just by ambient vibrations are continuously monitored by an accelerometer. The numerical treatment of the monitored accelerations allows identification of the 1$^{st}$ resonant frequency of the composite beam, which is evolving as concrete hardens. The E-modulus of concrete can thus be directly obtained from the monitored frequency. Besides the description of the overall setup, the results obtained in an experiment in which the concrete E-modulus was quantified also through static tests on the beam and via compressive tests in cylinders are presented and discussed.

## 1 INTRODUCTION

Evolution of the E-modulus of concrete since the instant of casting is of primary importance, not only to properly characterize material performance, but also to allow estimation of stresses that develop in concrete structures during early ages (Azenha *et al.* 2008, Azenha *et al.* 2009a). The existing resonant frequency-based methodologies (ASTM 2002, Jin *et al.* 2001, Nagy 1997) for estimating early age E-modulus of cementitious materials fail to fully accomplish this task, since they require specimens to be de-mouldable, and to have some mechanical strength to withstand the excitation necessary for measurements. In the case of ultrasonic pulse velocity-based methods (Malhotra *et al.* 2004, Reinhardt *et al.* 2004) measurements are possible since the instant of casting, but relation between the material E-modulus and the measured velocity is not as clear as in the case of resonant frequency methods. The present paper aims to create a variant to the traditional resonant frequency methods, allowing continuous concrete E-modulus measurement right after casting operations. For that purpose an experimental setup that consists of a simply supported beam made up of an acrylic glass tube, filled with fresh concrete, is presented. Natural frequency of the 1$^{st}$ flexural mode (with deflections in vertical direction) of this beam, excited by ambient vibration, is continuously monitored along time: (i) just after casting the identified frequency corresponds to that of the acrylic tube carrying the mass of unhardened concrete; (ii) during concrete hardening the beam endures composite behaviour, and 1$^{st}$ flexural frequency increases in correspondence to the growing concrete elastic modulus. By continuously determining the 1$^{st}$ frequency of vibration for the beam, it is then possible to directly obtain the E-modulus of concrete at each instant. Together with the proposed experiment, E-modulus was determined by static loading tests on the beam, as well as in concrete cylinders of the same batch, tested in standard compressive tests. This experimental campaign validates feasibility of the proposed E-modulus characterization method.

## 2 MODAL IDENTIFICATION USING AMBIENT VIBRATIONS

Before tackling with the experiment itself, the methodology of modal identification without recourse to forced excitation is briefly described.

The technique of ambient vibration for modal identification of civil engineering structures has been widely used since the 1980's. It consists on relying on the environmental vibrations induced by wind, machines, etc. to provide a dynamic excitation for the structures, thus allowing the identification of their natural frequencies upon measurement of acceleration time series (Cunha *et al.* 2007, Magalhães *et al.* 2008).

The selected methodology for identification of the resonant frequencies is the Peak-Picking method, in its 'output only' version. This method assumes that excitation of the structure (or element) under study can be idealized as a white noise, that is, a stochastic process with constant spectral intensity in all frequencies. Thus peaks of the response spectra coincide with peaks of the frequency response function, which in turn allows identification of the structural natural frequencies. In order to obtain the spectral density function of the beam response, the Welch procedure (Welch 1967) is used here.

A brief outline of the overall acceleration measurement and data processing procedures adopted in this paper reads as it follows:

- The response record of accelerations along time collected during the experiment is subdivided into several parts, with 15 minutes duration each. For each of these parts resonant frequencies are identified by applying the Welch procedure: the 15 minute long time series are divided in a group of smaller time segments, with 4096 points each and a 50% overlapping. In order to minimize leakage effects, Hanning windows (Maia *et al.* 1997) are applied to each of these 4096 point time segments. The windowed time series are then processed using a Discrete Fourier Transform, which results in a group of auto-spectra. These auto-spectra are then averaged, and the averaged auto-spectrum for the 15 minute period under study is obtained.
- All the $N$ averaged auto-spectra ($PSD$) obtained are then normalized, rendering a normalized auto-spectra ($NPSD$) according to

$$NPSD(w) = PSD(w) \Big/ \sum_{i=1}^{N} PSD(w_i) \tag{1}$$

where $w$ is the angular frequency. This procedure is essential as the averaged time series collected along the experiment correspond to distinct 15 minute periods, for which the ambient vibration may have had dissimilar intensity, thus conducting to distinct energy content in the spectra.

- The obtained $NPSD(w)$ are then included side-by-side in a colour frequency *versus* time graph, with the colours being proportional to the intensity of the power spectra (see example in Figure 5).
- In order to obtain a simple and automatic estimate of the 1st resonant frequency for a given period of acquisition (15 minutes in the case of this research), an average is made with the frequencies corresponding to the 40 points of higher energy of each spectrum, using the energy intensity as a weighting factor. By applying this to all averaged spectra, a resonant frequency *versus* time graph is obtained, which in turn can be used to obtain a plot of the concrete E-modulus *versus* time evolution.

## 3 EXPERIMENTS

### 3.1 *Test setup, experimental procedure and materials*

The experiment involves the use of a 2m long acrylic tube, with internal and external diameters of 92mm and 100mm, respectively. Thus, for the concrete to be properly casted its maximum aggregate size should be compatible with the 92mm internal diameter of the tube. The acrylic tube is drilled with 5mm diameter holes at specific locations: (i) at 100mm from the edges two holes exist, through which horizontal steel rods are passed to form two hinges, vertically supported on steel profiles, leading to a 1800mm span simply supported beam (see Figures 1 and 2); (ii) vertical steel rods are inserted through holes spaced 300mm from each other, to improve solidarization between concrete and the acrylic tube. The used steel rods have a nominal diameter of 4mm and an E-modulus of 180GPa. Two lids are used to contain concrete inside the acrylic beam (see Figure 1): on one of the extremities the lid was fixed; on the other extremity a removable lid was used to allow casting operations to be executed.

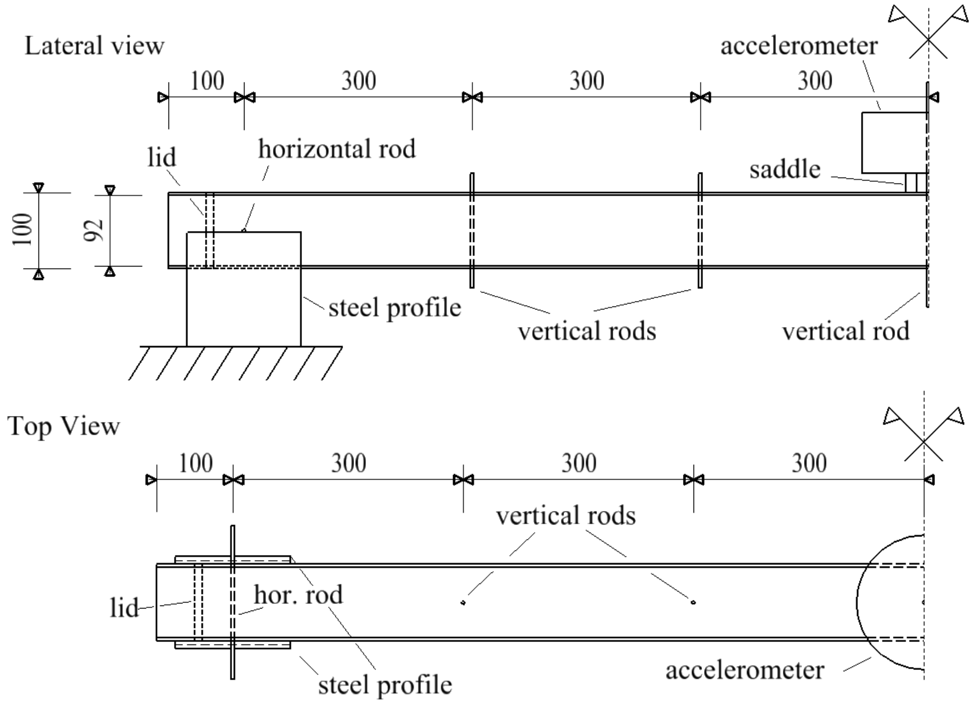


Figure 1. Lateral and top view of the experimental setup.

The use of ambient vibration implies that the levels of measured responses are very low, so the adopted sensors must have high sensitivity and low noise level, and the measuring system should provide a good resolution. In the pilot experiment considered here a CMG-5T force balance accelerometer from Guralp was used, which allows measurement of accelerations within a frequency band of approximately 0Hz up to 100Hz, and it has a sensitivity of 5V/g and a noise floor around 2μg. This sensor was connected to a GSR-24 recorder from Geosig that provides power to the sensor, performs the analogue-to-digital conversion of the measured signals using a 24-bits board, and stores the collected data in an internal memory card. The recorder was programmed to perform the acquisition of 15 minute time series with a sampling frequency of 100Hz, according to a predefined timetable. The accelerometer has a weight of 2.27kg, and it was fixed to the steel rod located at the beam mid-span. Figure 2 presents a photo with all the experimental setup (after casting), including the equipment used for the dynamic measurements.

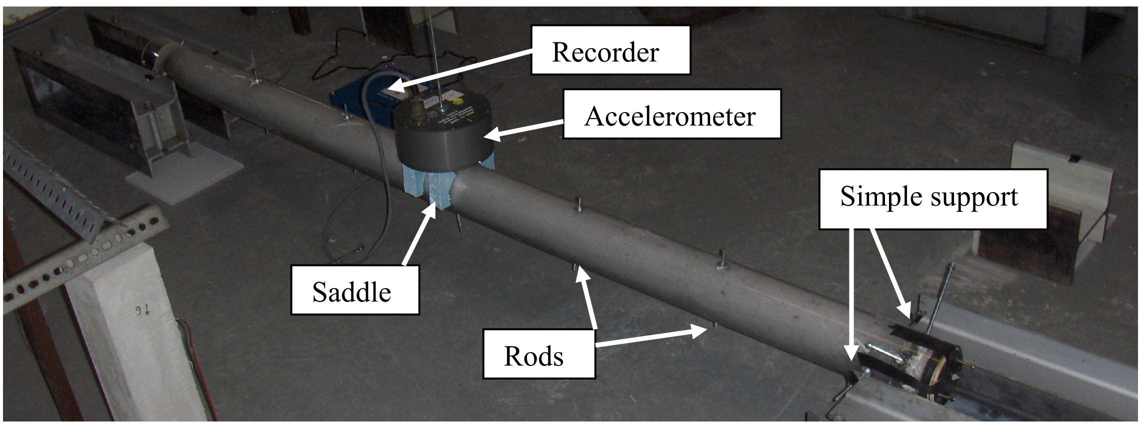


Figure 2. Photo of the complete experimental setup.

Casting operations were performed by placing the acrylic tube at a 45º angle with the horizontal, being concrete poured through the top extremity (with the lid previously removed). As casting advanced the tube was progressively inclined up to a 90º angle, and finally it was closed with the removable lid, ending back in the horizontal direction. The time elapsed between onset of casting and the start of acceleration acquisition was less than 15 minutes. The experiment took place inside a controlled climate chamber, with a constant temperature of T=20ºC and relative humidity of RH=50% for a total of 28 days.

At the age of 28 days a static loading test was performed with the composite concrete-acrylic beam, which consisted of sequentially placing steel plates with known mass on top of the accelerometer, and recording the corresponding mid-span deflections with two LVDT's. After this static test, which was conducted with loads well below the cracking load of the beam, further ambient vibration tests were conducted in order to check that the resonant frequency remained the same, and that no damage was induced to the composite beam.

In parallel to the beam tests, E-modulus of concrete was also evaluated at the ages of 0.75, 1, 2, 3, 7 and 28 days by performing compressive tests on standard cylinders (with a 15cm diameter and 30cm tall), cast with the same concrete batch and using three specimens per age. Prior to testing all specimens were kept in a curing chamber with T=20ºC and RH=100% .

In regards to the acrylic characteristics, its main properties were: E-modulus=3.3GPa, Poisson's coefficient=0.39 and density=1190kg/m$^3$. As far as the concrete is concerned, the mix is reproduced in Table 1.

Table 1. Mixture proportions of the studied concrete

| | Quantity (kg/m$^3$) |
|---|---|
| Cement type I 42.5 R | 419.8 |
| Mineral addition (calcareous filler) | 179.3 |
| Superplasticizer | 6.7 |
| Sand 1 (fine) | 416.2 |
| Sand 2 (coarse) | 315.3 |
| Gravel | 848.5 |
| Water | 174.5 |

### 3.2 *Estimation of concrete E-modulus with basis on measured frequencies*

Based on the measured resonant frequency corresponding to the 1$^{st}$ mode of vibration of the composite beam, it is necessary to establish the mathematical equations that allow calculating the actual E-modulus of concrete. Taking advantage of the symmetry of the beam, its geometry and characteristics can be schematically depicted as shown in Figure 3. In this figure, $\phi(x)$ is the vertical deflection mode, $x$ denotes the longitudinal coordinate, $\overline{m}$ is the uniformly distributed mass, $m_p$ is a concentrated mass applied at mid-span, $k$ is a spring constant (related to the vertical stiffness of the simple supports of the beam), $L$ is half of the span and $\overline{EI}$ is the distributed flexural stiffness of the beam.

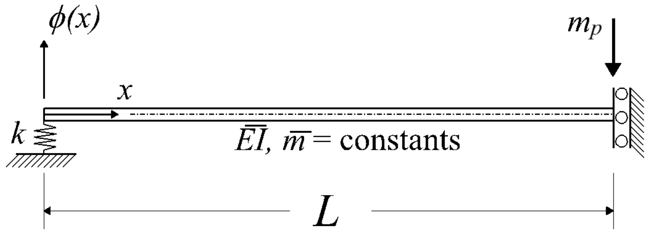


Figure 3. Scheme of the simply supported beam

By applying adequate boundary conditions to the free vibration equation of the beam (Clough *et al.* 2003), the equation that expresses the resonant angular frequency $w$ is (Azenha *et al.* 2009b):

$$-1/(2k)\Big[\ \overline{EI}\,a^3\sin(aL)^2 w^2 m_p + 2\cosh(aL)k\,w^2 m_p\sin(aL) + \cosh(aL)^2 w^2 m_p\,\overline{EI}\,a^3$$
$$+2\left(\overline{EI}\right)^2 a^6\sin(aL)\cosh(aL) - \overline{EI}\,a^3\sinh(aL)^2 w^2 m_p + 2\cos(aL)\left(\overline{EI}\right)^2 a^6\sinh(aL) -$$
$$4\cos(aL)k\,\overline{EI}\,a^3\cosh(aL) + \cos(aL)^2 w^2 m_p\,\overline{EI}\,a^3 + 2\cos(aL)w^2 m_p\,\overline{EI}\,a^3\cosh(aL) - \tag{2}$$
$$2\cos(aL)k\,w^2 m_p\sinh(aL)\ \Big] = 0 \quad \textit{with} \quad a = \sqrt[4]{\frac{w^2\overline{m}}{\overline{EI}}}$$

So, at a given instant, based on the measured resonant frequency $f$ (or equivalently $w=2\pi f$) provided by the modal identification, it is possible to evaluate the distributed flexural stiffness of the beam $\overline{EI}$ from equation (2), since all other parameters are known. Furthermore, as $\overline{EI}$ can be expressed as the sum of the distributed stiffnesses $E_aI_a$ for the acrylic tube and $E_cI_c$ for the concrete, the E-modulus of concrete can be obtained directly from:

$$\overline{EI} = E_a I_a + EI = 3.3\times10^9\,\frac{\pi\left(0.1^4 - 0.092^4\right)}{64} + E\,\frac{\pi\,0.092^4}{64} \tag{3}$$

All these procedures were included in a developed software for modal identification, creating a package that allows direct evaluation of concrete E-modulus with basis on the acceleration records.

# 4 RESULTS AND DISCUSSION

## 4.1 *Tests conducted at the age of 28 days*

As mentioned before, three distinct methods of measuring concrete E-modulus were applied at the age of 28 days: modal identification, a static loading test and tests on cylinders.

Regarding the modal identification, the 1st resonant frequency of the system was $f$=38.4Hz. By applying the known data into equations (2) and (3), the computed E-modulus at the age of 28 days is E=33.6GPa. The relevant information used for this calculation was: (*i*) $L$=0.9m; $\overline{m}$=17.0176kg/m; $m_p$=1.135kg (half of the accelerometer's mass); $k=\infty$ kN/m (rigid simple support).

The static loading test at the age of 28 days, with two cycles of loading/unloading of 30kg (using weights of ~5kg each), led to an observed global average of the mid-span deflection per unit of applied mass of 0.0098mm/kg. With due account to standard elastic formulae relating mid-span deflections of a simply supported composite beam with a concentrated load, one gets a E-modulus for concrete at the age of 28 days equal to 33.3GPa. It is worth mentioning that the resonant frequency of the composite beam after the static loading test remained $f$=38.4Hz, showing that no damage was induced to the beam during the static loading test.

The average value of E-modulus computed from the compressive tests in concrete cylinders is 33.4GPa.

There is a remarkable resemblance between the E-modulus calculated with the three techniques, which mutually validate themselves, thus proving robustness of the proposed methodology for concrete E-modulus identification.

## 4.2 *E-modulus evolution until the age of 28 days*

Before actually discussing the results obtained for the initial monitoring periods, a remark should be done on the support conditions of the composite beam at this stage. The hinged supports mentioned in Section 3.1, which were described as horizontal rods supported on steel profiles, did not have the same configuration throughout the whole experiment. In fact, they were changed at the age of 14.9 days, according to the scheme of Figure 4: a) initially there was a small cantilevered part of the rod between the acrylic and the supporting steel profile; b) after 14.9 days it was decided to change the support conditions, in order to achieve vertically rigid supports. The observed resonant frequencies of the beam shifted with the change of support conditions. Nonetheless, these changes were explicitly considered in the estimation of E-modulus through the methodology described in Section 3.2. For further details on the estimation and validation of the stiffness of the supports until the age of 14.9 days, see Azenha *et al.* (2009b).

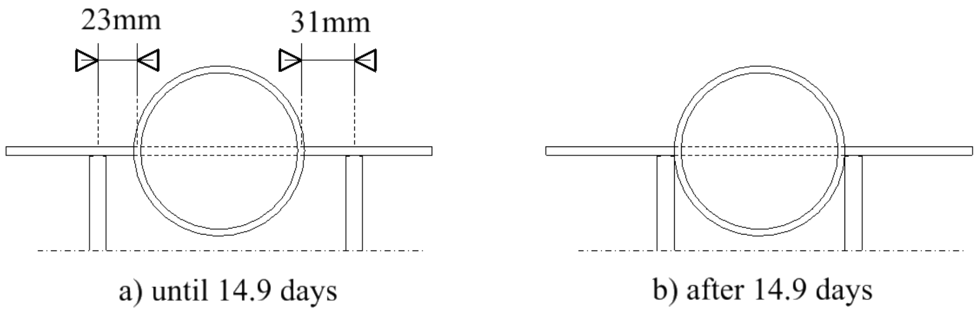


Figure 4. Support conditions throughout the experiment – cross-sectional view

The representation of the frequency spectra measured until the age of 48 hours can be seen in Figure 5. This is the period in which the resonant frequency varies the most, starting at ~8 Hz during the concrete dormant period (it corresponds to the resonant frequency of the acrylic beam, filled with fresh concrete without stiffness), which lasts for 3.6 hours. After the dormant period the resonant frequency rapidly grows up to ~20Hz at the age of 10 hours. From then on frequency changed rather more slowly, reaching *f*=26.1Hz at the age of 14.9 days.
The change in support conditions at the age of 14.9 days instantly shifted the 1$^{st}$ frequency from *f*=26.1Hz to *f*=38.3Hz, with the final resonant frequency at 28 days being *f*=38.4Hz (negligible stiffness evolution between 14.9 and 28 days, as expectable).

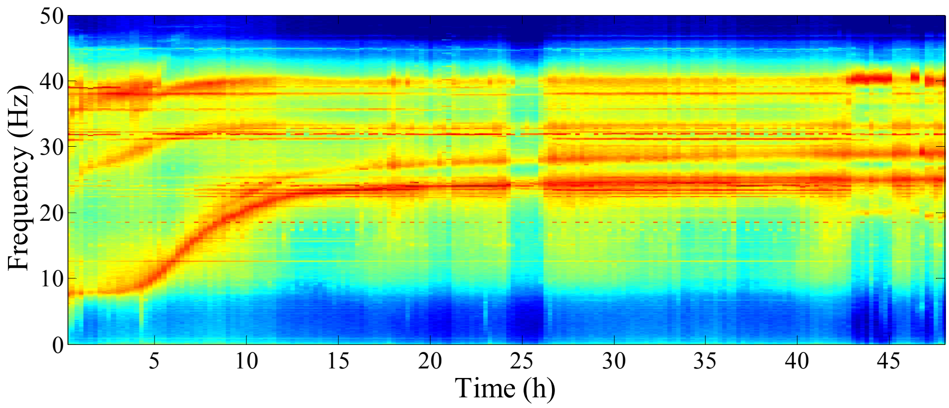


Figure 5. Measured frequency spectra until the age of 48h

With the information gathered from the resonant frequency evolution it is possible to plot the evolution of concrete E-modulus along the experiment for the period of 0-72 hours (Figure 6), and for the period of 0-28 days (Figure 7). In Figures 6 and 7 the results obtained from the compressive testing of cylinders are plotted also for comparison.

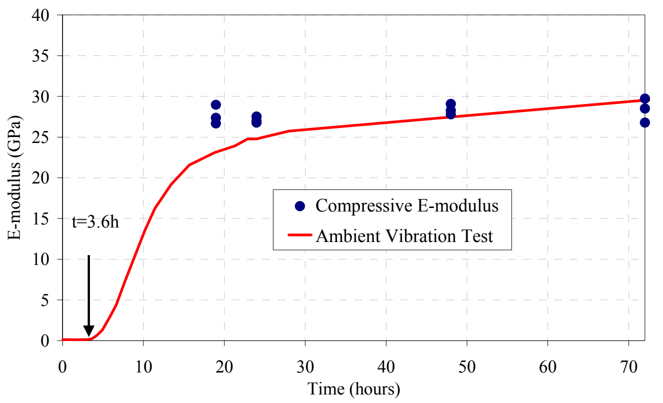


Figure 6. Concrete E-modulus evolution until the age of 72 hours

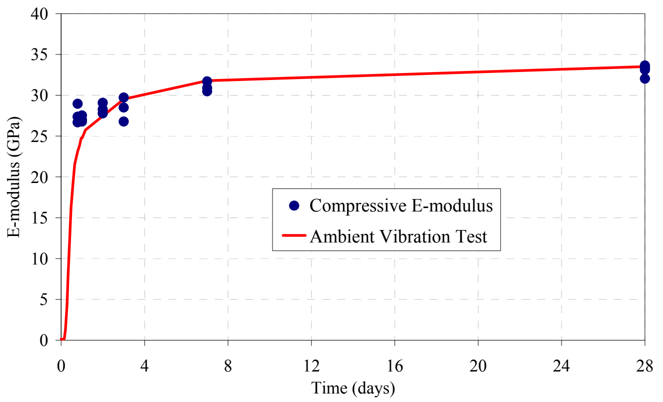


Figure 7. Concrete E-modulus evolution until the age of 28 days

From observation of Figures 6 and 7 an excellent coherence is detected between the two testing procedures for ages above 1 day. However, for the ages of 0.8 days and 1 day the concrete E-modulus obtained through the proposed methodology are lower than those obtained through compressive testing. One should however be aware that specimens with different sizes and curing conditions are being used: the ambient vibration test pertains to a 92mm diameter cylinder cured inside a 4mm thick acrylic formwork, whereas standard compressive testing regards to specimens with a greater diameter (150mm) cured inside a 26mm thick plastic formwork. These differences in specimen size and boundary conditions can lead to different temperature development in the two cases (with higher temperatures in the 150mm diameter specimens), which due to the thermally activated nature of cement hydration reactions can lead to distinct E-modulus evolutions at early ages (with faster development in the compressive test cylinders). The differences in hydration tend to fade as concrete ages, showing negligible effects after the age of 1 day.

## 5 CONCLUSIONS

A new methodology that allows continuous measurement of concrete E-modulus since casting has been proposed in this paper. The methodology relies on the continuous monitoring of the 1$^{st}$ resonant frequency of a beam made of acrylic filled with concrete. E-modulus of concrete can be directly estimated from the measured resonant frequency, thus yielding a continuous curve that captures: (i) the duration of the dormant period, (ii) the steep evolution of concrete E-modulus during the first hours after casting and (iii) the slower evolution in the subsequent periods. This experimental technique has the advantage of being completely autonomous, avoiding the necessity of operator assistance during the testing period. It is also entirely passive, as the ambient vibrations are usually enough to create the necessary excitation for the resonant frequency of the beam to be identified (in opposition to the case of classical resonant frequency methods).

A pilot experiment has been conducted with a 1.8m long composite beam, which was continuously monitored, with the E-modulus of concrete being also estimated with recourse to two other techniques: static loading of the beam and standard compressive testing on cylindrical specimens. The outcome of the three testing procedures points to the feasibility of the ambient vibration technique to be used systematically in the continuous quantification of concrete E-modulus since casting. This kind of testing procedure has potentialities that are currently being explored, in regard to the study of the effect of mixing proportions of concrete in the structural setting time, as well as in the stiffness development. In what concerns to construction site applications, this methodology is bound to be useful in defining formwork striking times, namely in the case of continuous slip-forming.

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